Spatial planning of public charging points using multi-dimensional analysis of early adopters of electric vehicles for a city region

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Abstract

The success of a mass roll out of Plug-in electric vehicles (PEVs) is largely underpinned by establishment of suitable charging infrastructure. This paper presents a geospatial modelling approach, exploring the potentials for deployment of publicly accessible charging opportunities for consumers based on two traits – one, trip characteristics (journey purpose and destinations); two, PEV adoption intensity. Its applicability is demonstrated through a case study, which combines census statistics indicating lifestyle trends, family size, age group and affordability with travel patterns for an administrative region in the North-East England. Three categories of potential PEV users have been identified – 'New Urban Colonists', 'City Adventurers' and 'Corporate Chieftains'. Analyses results indicate that Corporate Chieftains, primarily residing in peri-urban locations, with multi-car ownership and availability of onsite overnight charging facilities form the strongest group of early adopters, irrespective of public charging provision. On the other hand, New Urban Colonists and City Adventurers, primarily residing in the inner-city regions, show potentials of forming a relatively bigger cohort of early PEV adopters but their uptake is found to be dependent largely on public charging facilities. Our study suggests that effective PEV diffusion in city-regions globally would require catering mainly to the demands of the latter group, focussing on development of a purpose-built public charging infrastructure, both for provision of on-street overnight charging facilities in residential locations and for fast charging at parking hubs (park and ride, amenities and commercial centres).

Keywords: charging infrastructure; electric vehicle; GIS; public charging; socio-demographic

1. Introduction

Alternative fuelled vehicles (AFVs) are expected to play a major role in decoupling transport's ~93% dependence on liquid fossil fuels, through diffused adoption of both Plug-in electric vehicles (PEVs) and hydrogen fuel cell vehicles [1]. PEVs in particular, including both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have the potential to improve the energy and environmental landscape of personal transportation over the next decade. However, absence of a proactive plan and schedule for charging infrastructure is a major impediment to mass market adoption, particularly pertinent to BEVs due to their sole dependency on electricity, range limits, and long recharging time [2]. In this context development of a coherent policy in the area of electric mobility (i.e. E-mobility) is being increasingly considered as a viable investment in offsetting transport-related climate change effects associated with conventional vehicles over near-term [3]. An analysis of developments in electric vehicles before and after 2005 suggests the diffusion of E-mobility configuration in recent years to be largely dependent on infrastructural investments [4]. Consumer surveys from across different global markets indicate that lack of refuelling infrastructure is going to be a major deterrent for adoption of AFVs [5,6]. The UK Department for Transport (DfT) has set up an Office for Low Emission Vehicles (OLEV), committed to development of an ultra-low emission vehicle market – facilitating better energy security while addressing issues related to CO_2 emissions and air quality in cities [7]. However, the current drive for securing the future of mobility through electrification, at least over the short to medium term, is faced with technological, infrastructural and behavioural hurdles that need to be overcome in order to enable mass market penetration [8].

Development of adequate public charging opportunity has been proposed as a viable compromise in effectively mitigating the range anxiety rather than focussing on the development of longer-range vehicle capabilities [3,9]. Interesting findings, based on optimal charging algorithm for locating the service points while minimising the charging costs, reveal distinct charging infrastructure strategies for PHEVs and BEVs. While PHEVs tend to have lower returns from 'non-home' i.e. public charging infrastructure (in terms of efficiency savings and operating costs reductions), BEVs on the other hand show increased feasibility from such investments [2]. The demand for optimal public charging point locations has led to consortiums of companies in the transport, energy and power electronic sectors working together on projects connected with the initiation of commercial charging terminals for BEVs, as well as fast charging public stations [10]. The C40 Electric Vehicle Network (C40 EVN), based on policy analysis exercise on the deployment of PEV charging infrastructures in C40 cities (a group of the world's largest cities) has facilitated the successful introduction of PEVs through collective municipal actions, including planning and deployment of charging infrastructure, streamlining permitting processes associated with new installations, providing monetary and non-monetary incentives and mobilising demand for PEVs in city fleets [11]. The C40 study assessed the potential barriers (policy, technological, economic, etc.) to the deployment of electric vehicle charging point infrastructure.

Currently the debate on the best set up for the provision of public charging point (PCP) infrastructure is wide open, given the technology and its implementation plan are still in their infancy. Better understanding of present and future PEV users through numerous market deployment scenarios, both at the European level [12,13,14] and globally [5,6,15,16], have been developed through dedicated literature surveys, focus groups and expert elicitations to assist in informed political decisions towards adequate policy interventions for supporting the PEVs (both PHEVs and BEVs) markets. Charging demand of an early PEV market in Beijing has been estimated using an assignment model on the basis of the number of local refuelling stations (conventional vehicles) and communal/public parking spaces [15]. A system dynamics model of the UK take-up of PEVs has provided modest market share forecasts, expected to evolve over the next 40 years [17]. A diffusion model, utilising multi-criteria analysis and choice modelling, has been applied to estimate the adoption of PEV technologies spatially across heterogeneous mix of Australian consumers through to 2030 [16]. Overall, it is envisaged the uptake of PEVs will largely depend on two crucial factors – a. oil price fluctuation; and b. consumer acceptance. In the UK, a London-wide PEV charging network is being set up as part of the 'Source London' initiative, with an aspiration for establishing London as the PEV capital of

Europe (with a target of installing 25,000 charging points by 2015, including 500 on-street charging points and 2,000 charging points in off-street public car parks and Tube/ Over ground rail station car parks) [18]. Based on the UK government projection, there will be acceleration in the uptake of PEVs nationwide from 2015-2020 [19], henceforth increasing the demand for a more spatially optimised charging point infrastructure over this period. The market will then have the opportunity to expand as the acceptance of the new technology grows and its range anxiety issues decline. In the short term at least, the majority of recharging in the UK is expected to occur at home, with further recharging opportunities provided in public charging bays, piloted through government schemes such as ‘Plugged in Places’ under the Carbon Plan or at work if the employers join these schemes [19]. Similar trends are reflected in global studies, suggesting a steady rate of growth in PEV uptake, with most users commuting short distances from suburban locations [5,6,15].

Limiting the scope for developing an implementation strategy for PCPs is the fact that till date there is little information on profiling of early PEV adopters. A recent survey in the US has identified potential socio-technical barriers to consumer adoption of PEVs, particularly highlighting the perceptions and preferences of technology enthusiasts as potentials early adopters [3]. In the UK, a statistical methodology based on hierarchical cluster analysis to census data, characterising the age, income, car ownership, home ownership and socio-economic status, has been applied to identify potential early adopters of a range of AFVs (predominantly for the uptake of PEVs) using a case study for the city of Birmingham [8]. Over the years public charging points are expected to generate greater awareness and marketing potential for the roll out of PEVs [18]. However, recent insight into the business case of public fast chargers for PEVs indicate the current market outlook to be uncertain for triggering a large scale roll out, unless investment costs can be severely lowered [20]. During the current phase of austerity in public spending by governments this however requires well-informed decision making on the choice of strategic locations upfront for installation of cost-effective charging points, especially with regard to targeting areas of potential PEV uptake. This is vital to creation of a region-wide charging network independent of individual/ household charging facilities. In this regard a GIS-based multi-criteria decision support approach - combining several ‘expert-weighted’ economic, social, environmental and transport-related traits for European cities (scoped at cities level within EU27) – has been applied recently to assess the PEV market penetration up to 2030 [21]. However, the importance of range anxiety in consumer decision making, involving neighbourhood level spatial infrastructural data (e.g. accounting for multiple-parking capacity for specific dwelling location) alongside geographically-enabled travel pattern data (e.g. distance, journey purpose, etc.), has not been investigated spatially in any previous studies [13].

The aim of this paper is to develop a methodological approach for multi-dimensional spatial analysis addressing the aforesaid knowledge gap, combining the underlying socio-economic traits and trip characteristics (journey types and origin-destination) for prioritising the demand-based public charging hotspots. Keeping the scope of the assessment essentially as urban its applicability is demonstrated through a case study for a city-region in the North-East England. The multi-criteria spatial analysis considers both residential premises and commercial centres spanning across the inner-city and out-of-town locations in the case study region. The spatial model predicts suitable sites/ zones for installing purpose-built PCPs within the existing built-infrastructure on the basis of socio-economic traits and trip characteristics. In the subsequent section, viable recommendations have been made based on our results, supporting mass uptake of transport innovation through adequate infrastructure planning, specifically catering to the demands of early adopters lacking overnight, off-street residential parking facilities.

2. Methods

2.1 Data analysis and assumptions

As a first step, a hierarchical data structure for multi-dimensional spatial analysis was developed based on a number of criteria to ascertain the most appropriate location of PCPs. A shortlist of key determinants of PEV adopters was generated utilising recent literature [8,6,22,23,24,25], combining the underpinning household demographic and macroeconomic traits. The main features included – gender, age, occupation, level of household income, number of vehicles owned, environmental awareness, interest in new technologies, sensitivity to government incentives, and knowledge about fuel economy. This led to acquisition of required data from a range of census information statistics as detailed below.

Table 1 lists the key variables applied to this analysis, the rationale for including them is based on the literature reference along with their information source. As can be noted, the majority of spatial information on socio-demographics, accessible as digitised map layers with boundary information in GIS format, was obtained from the UK Census Dissemination Unit (Casweb) [26]. However, the trip origin-destination data could not be collated within the Casweb system and was alternatively accessed from the Centre for Interaction Data Estimation and Research (CIDER) [27], mainly covering information on traffic flows pertaining to commuting patterns. The latter dataset enabled generation of intra-regional origin-destination statistics used in the spatial analysis (Section 2.3.1). The following four constraints were applied to identify the potential for setting up PCPs which duly accounted for the emerging trends in potentials for early adopters charging privately at home. Adequate assumptions were made while interpreting census information from a particular selection of data sets, as described later where applicable. This was deemed essential due to the limitation of available information in projecting the PEV uptake potential directly.

2.1.1 Off-Street Parking

As common to several European and global cities, the majority of UK cities have less than 40 percent of urban households with off-street parking availability though around 70 percent of suburban residential households have off-street parking availability [28]. For households that do not have off-street (garage) parking, and those who park on the street or in public garages, PCPs are going to be key to early uptake [6,29]. Although off-street home charging, utilising a 240 V/13 A (or 16 A) connection with a switchable socket and surge protection device, has been considered as common route for charging by majority of first generation PEV users [30], a more recent study in the UK suggests that current planning policies often limit the number of off-street parking places, and in many rented properties, installing charging sockets with required specification could be complicated [31]. These issues are going to be reverberated in cities in other parts of the world as well. We have therefore taken a conservative estimate in locating the PEV charging infrastructure - for PHEVs, assuming 50% of consumers would charge off-street at home; for shorter range BEVs, assuming 90% of consumers would charge on-street, i.e. dependent mainly on PCP availability [13]. While populating the neighbourhood level infrastructural data in the spatial model we assumed that only detached and semi-detached households have off-street parking while remaining residents park their vehicles on-street.

2.1.2 PEV User Demographics

The UK Office of National Statistics has generated 14 categories of occupations, ranging from employers in large organisations to those who have never worked and long-term unemployed [26]. A recent study derived the representative socio-economic status of early adopters for a UK city (assuming direct association with higher income levels) by combining two occupation groups – ‘Higher professionals’ and ‘Lower managerial and professionals’ [8]. Extending this approach further, the potential PEV adopters in our study were assumed to be representing the top 3 rankings of these socio-economic categories, including ‘Employers in large organisations’, ‘Higher managerial occupation’ and ‘Higher professional occupations’. It was assumed that these cohorts in turn would lead the way to mass market adoption of PEVs.

2.1.3 Young Professionals

Recent industry surveys for the EU and the US suggest that early adopters of BEVs will generally be male, between 18 and 34 years of age [6]. Further, young professionals are viewed as being strongly attached to technology and the media, and are known to have early adoption traits [8]. Although recent studies have highlighted the extension of this age-group to include both early- and middle-aged professionals (20-55 years) [8,23] the latter, relatively older age group of professionals, has been considered as more affluent (and owning semi-detached or detached houses with off-street parking) and thus having lower demand for PCPs. In the data selection process of census area statistics provided by Casweb, data sets categorised by age groups can be matched to economic demographics. However, the age groups concerned are particularly large (e.g. 20-24, 25-34, 35-54). Therefore, the age band of the demographic group representing young and professional (or young urban professional), referring to members of the upper middle class in their 20s and 30s were considered. Along these lines, the age boundaries of 20-24 and 25-34 were chosen to symbolise young urban professionals.

2.1.4 Socio-economic Classification

A recent study for the UK HEV adopters (1263 participants) has reported 39 percent with household income over £48,000 net per year (~$78,000 USD, 2011), and 58 percent possessing an extra car [24]. Although a PCP infrastructure framework has already been developed in the UK for London as part of the London Strategy [32] similar guidelines are still not available for other regions. We therefore adopted the London Strategy with slight amendment to the socio-economic characteristics of the region (for example the 'global connection' category was omitted to develop a more generalised classification since this was considered specific to the most affluent features of areas in central London). On this basis, the resident population was divided into the following three cohorts, essentially reflecting their distinct characteristics – New Urban Colonists; City Adventurers; Corporate Chieftains. These three cohorts were synthesised from the mosaic types of current PEV (both PHEVs and BEVs) users in London [32] and is considered representative of the majority of European cities with similarly short driving ranges and densely populated urban areas. These population groups were geographically combined with the local socio-demographic information, utilising already established set of criteria for early adopters as identified in recent literature from cluster analysis [8]. 'New Urban Colonists' were assumed to include small households (with either single or couple with no children) as well as other households (implying multi occupancy households). The emphasis on 'single or couples' was assumed to provide a distinct classification.

'City Adventurers' were considered as young professionals and 'Corporate Chieftains' were represented by senior management professions with detached houses.

The spatial location of these cohorts in a specific study location could be established through selection of appropriate household composition from published national statistics, for example in the UK this information can be acquired from the National Statistic Socio-economic Classifications (NS-SeC) [33]. It was anticipated that some of the traits between the three cohorts would be overlapping. To account for this anomaly, census data with high ranking NS-SeC classifications and the age groups of 20-24 and 25-34 were chosen as representative of all three cohorts. Further, the data on Corporate Chieftains was collected by gathering separate information from ward totals of detached housing and the assumption that managers belonged to the classification for the highest NS-SeC category ranking. This is along the lines of an earlier study [8] who also used socio-economic status as an indicator of income by assuming occupation group 'professionals and managers' to be representing those expected to have a higher income than other occupation groups. In previous studies education has been considered as an important factor in determining AFV uptake potentials [23,34]. However, a recent study from Birmingham (UK) reported some wards with high student population, having higher education levels but not affluent home-owners, yet possessing multiple cars in the household [8]. Such contradictory results demonstrate the need for extra caution in applying specific demographic characteristics to a given area while assessing the PEV adoption trends, in particular for determining locations of PCPs. Based on this argument education level was not considered a reliable trait while evaluating early adopter potentials and hence omitted from subsequent spatial analysis in profiling of early adopters of PEVs in this study.

2.2 Case study

This section demonstrates the applicability of the spatial modelling framework described in Section 2.1 through a case study based in the Tyne and Wear County of the North-East England. The study region comprises of five local authorities (South Tyneside, North Tyneside, Newcastle, Gateshead and

Sunderland) with a total population of over 1 million [33]. It has been considered appropriate on its merits of being a suitable test bed for evaluation of the regional spread of early adopters of PEVs, relying on both private and public charging points. Pertinent to this, the region is currently witnessing a huge push from the UK government funded 'Plugged in Places' scheme on promotion of low-emission vehicles [7,19]. In addition, crucial to the scope of this study in promoting public charging infrastructure at workplaces and publically available charging locations, the proportion of travel to work by car in the Tyne and Wear region is reported as 58.7 percent, well-within a comparable range of national average of 61 percent reported for the UK [26].

2.3 Spatial Analysis

While Section 2.1 enabled assignment of neighbourhood level spatial infrastructural data (dwelling sizes, PEV early adoption traits, Off-street charging etc.) this section concentrates on populating geographically-enabled travel pattern data for locating the PCP hotspots for the case study site. Essentially this is based on the following two metrics – one, trip destination; two, PEV adoption intensity. This selection was based on recent findings suggesting geographical differences in PEV uptake to be primarily influenced by driving distances and socio-economic characteristics of households [8,16]. Further, the two metrics enabled a representative mechanism for spatially analysing the impact of PEV driving patterns for the purpose of locating the potential hotspots for PCPs. This follows similar methodology adopted in recent studies [8,27] to overcome the anomalies in previous studies where PEV vehicle flows were estimated as a subset of the conventional vehicle flows, assuming homogenous PEV adoption rates within a region, ignoring the underlying traits of PEV users. A dedicated spatial software tool (ArcGIS v10) was used to integrate the GIS-enabled demographic and travel datasets acquired at the Super Output Area Level (SOA). The SOAs in the UK represent the smallest geographic units for disseminating robust census statistics while the confidentiality of individual census returns remains preserved [22]. Various spatial layers were computed from census statistics and compared between different areas of the Tyne and Wear region through application of geoprocessing tools to establish the favourable traits, including distribution of affluent households (characterised by detached houses, multi-car ownership), park and ride facilities, and regional centres. The latter comprising of large industrial facilities, large retails and business parks, amenities and prominent transport hubs (including the regional airport) (Figure 1). This allowed for deriving relationships in the data that could not have been readily apparent in databases or spread sheets. GIS outputs with graduated colour ramps highlighting key areas of interest (i.e. hotspots) were generated for evaluation and interpretation of the spatially varying totals between wards across the study domain.

<Place Fig 1 here>

The following sections describe the steps involved in trip characterisation for early EV adopters.

2.3.1 Intra-regional origin-destination mapping

Commuting and other major trip purpose journeys were identified for the study region using the ward census data. While analysing commuting patterns the focus was mainly on car trips and not on overall commuting patterns from all modal forms. This was done to assess the implementation of charging infrastructure for personal transport users (mainly cars). The origins and destinations of all commuting journeys were only calculated within the case study region. For commuting trips originating outside the study domain only the portion of the trip falling within the study boundary were considered for consistency in finding suitable charging point locations. Following the recommendations of a recent study [9], the spatial analysis coupled vehicle range and trip length as a function of trip journey purpose to locate PCPs. Constraining the origin-destination mapping by BEV range requirements was considered relevant for ensuring the commuters' concern on non-reliability of BEVs for essential trips. On this basis mappable information of the most likely destinations for BEVs were generated, thus facilitating the derivation of viable PCP installations in areas with high proportions of car commuting trips.

2.3.2 Electric vehicle adoption intensity

This step utilised the socio-economic demographics, acquired following the criteria described in Section 2.1.4, to determine the spatial distribution of New Urban Colonists, City Adventurers and Corporate Chieftains in the case study region. These were considered as early uptake 'hotspots'; the former two groups suggested to be relying heavily on deployment of PCPs [33] while the latter group was assumed to only use PCPs, especially those located at workplace, for top-up and emergency charging. The outcome of this analysis informed zoning of suitable charging point locations, both within the residential areas, and the earmarked parking hubs and commercial centres. The feasibility assessment followed the recently published UK National Planning Policy Framework guidance for green transport (i.e. potential for reducing environmental impact, mainly CO_2 emissions compared to equivalent standard vehicles depending on the embodied energy of the vehicle and the source of the electricity) on encouraging local authorities in incorporating PEV charging infrastructure at suitable sites as well as developing policies for embedding recharging infrastructure within new workplace developments [35].

2.3.3 Weighted overlay analysis

This step assessed the strategic locations for PCP installations, taking into consideration the multi-criteria assessment underpinning successful deployment and usage of these facilities. The key constraint was in making the choice of public charging infrastructure (fast or trickle charging) that would allow PEV users to recharge their batteries at varying rates, depending on trip purpose and parking duration. A recent study for the US, utilising a simulation-optimisation model to evaluate the PCP deployment strategies, considered location of trickle charging (typically rated at 220V and between 15 and 30A) to be ideal for parking lots and less effective at dedicated charging points since unlike conventional refuelling stations the availability of fast charging (DC high-voltage ~ 400–500V) at such sites becomes paramount for avoiding excessive waiting time. To compensate for the latter, previous studies [27,36] have recognised the need for multiple charging stations at a single location to capture a large flow of PEVs.

The layers of spatial information were overlaid to assess the favourable hotspots for PCP infrastructure. In order to reduce the investment costs it was considered necessary to first filter out the zones with majority of charging occurring privately on off-street premises; eliminating the cohort with least dependence on public charging consumer share. For this purpose, multi-criteria evaluation parameters were established for both public and private charging categories through combination of data layers generated in Sections 2.3.1 and 2.3.2 (Table 2). An integrated analysis was performed using the weighted-overlay technique in ArcGIS Spatial Analyst toolbox [37]. It is important to note that the Weighted Overlay tool accepts only discrete raster (integer values) as inputs. This makes it possible to perform arithmetic operations on the raster that originally held dissimilar types of values. For this purpose all the spatial information was first converted into classified datasets using raster pre-processing tools. The input raster were weighted by importance and added together to produce an output raster. A discretised evaluation scale from 1 to 10 (with 10 being the most favourable) was applied to represent the level of suitability of the locations for both private charging users and for installing PCPs.

2.3.4 Ground validation of multi criteria assessment

A series of consumer surveys were conducted as part of ground validation exercise to ascertain the reliability of the predictions made through weighted overlay analysis. This involved interviewing a sample population by splitting the case study area into four sub regions based on PEV adoption intensity following a recent approach applied to consumer testing of PEV technology diffusion [16]. The interview questionnaire involved acquiring relevant information for validating some of the outputs from the GIS mapping, typically asking the consumers' education level, gender, age, interest in green technologies, number and age of vehicles owned, average travel distance and time, willingness to install charging socket at home, availability of off-street charging facility.

3. Results and Discussions

3.1 Spatial analysis of potential PEV users

3.1.1 Origin-destination dependence

Outputs from the first step analysis of commuting patterns of car users in the region provided a clear indication of possible destination areas for potential PEV users. This enabled an assessment of the feasible zones for locating the PCPs. For this purpose ward-level commuting totals were split up into five class intervals to cover the bulk of the commuting trips into each ward (Figure 2). These were then used to symbolise the varying levels of commuting destination levels across the region. This was generated by dividing the maximum car commuting ward totals by the number of classifications necessary to show clear results. Car commuting hotspots (darker tone in Figure 2) were found to have over 78 percent car use as compared to a mean of 55 percent noted across the case study area. This indicates the potentials for PCPs installed in these locations in encouraging early PEV uptake due to the high proportion of car commuting dependence in the ward area.

The largest frequency came from smaller total commuting destination totals which were normally under 2000 car commuters. These wards symbolise residential areas, to which fewer people commute. At the far end of the scale four wards having very large car commuting totals were noted, representing central workplace areas to which a large majority of the region's working population commute to. Apart from this the major car commuting totals on the periphery of the two town centres (Sunderland and Gateshead) were mainly attractors of employees commuting to a large car manufacturing plant and several out-of-town shopping malls. This large total of car commuting destination trips to these remote locations is further augmented by the lack of availability of public transport. This pattern is typical of the majority of global cities with limited access to public transport availability to out-of-town commercial hubs and industrial parks. From our analysis it appears developing a work-based charging infrastructure would encourage employees working in this zone to be early PEV adopters. This is along the lines of current focus in promoting workplaces as the second main pillar of the UK plug-in vehicle recharging infrastructure [35]. It has been considered more applicable to Plug-in Hybrid Electric Vehicles (PHEVs) or Extended-Range Electric Vehicles (E-REVs), as these may need a different pattern of charging to deliver their maximum environmental and financial benefits, making the benefits of workplace top-up recharging potentially significant [7].

<Place Figure 2 here>

It is noteworthy that some city centre areas (in particular for Newcastle) show low percentages of car commuting trips compared to other modal choices. This is in agreement with finding from the Birmingham study [8] which also reported higher use of public transport while travelling to work in the inner-city wards. However, we note that this area is also attractor to car trips with a number of regional centres (see star shapes in top-centre locations in Figure 1), primarily leisure and shopping activities within the city centre. Locating PCPs at these sites would encourage car users to use these facilities, specifically if they are subsidised over the weekends. On the other hand, supermarkets and large retail outlets can become popular charging points as they can be incentivised through their promotional offers during twilight shopping hours.

3.1.2 Socio-economic dependence

Analysis of the socio-demographic GIS layers, generated from census data, enabled locating our three earmarked cohorts of residents in the region spatially. This analysis was conducted in several stages. The first step involved locating the specific areas where New Urban Colonists were most concentrated.

<Place Figure 3 here>

From Figure 3 it can be noted that the highest density of New Urban Colonists is located mainly in the North of the region, typically representing small families in the suburbs of Newcastle. Further, two areas that stand out from the trend of early uptake groups were found to be located in North Tyneside (middle-east zone on the map). Evidently, this reflects the fact that greater part of the resident population living in a household either singly or as a couple without children, prefer to live in the inner suburbs of the major city centre i.e. Newcastle, compared to other areas in the region. Therefore, the likelihood of early adoption of PEVs in this socio-economic category would strengthen the case for installing more charging points in this zone compared to other metropolitan districts in the region. This characteristic has spatial resemblance to the Birmingham study, suggesting majority of the wards (almost 60 percent) favouring the uptake to be located furthest from the city centre [8]. A general pattern emerging from these studies, that can be extended to other cities across the globe, suggest hotspots of early PEV adoption intensity to be dominant in the inner suburban pockets, closer to a major city (i.e. <15 minutes of travel time).

<Place Figure 4 here>

The next step analysis involved classification of City Adventurers mosaic type in the Tyne and Wear region. Due to the high NS-SeC rating when collecting the census data, the largest concentrations of the City Adventurers were mostly located in similar areas to the New Urban Colonists in Newcastle and on the mid-eastern flanks, albeit representing greater population densities (Figure 4). The neighbouring districts were again noted to make only a minor contribution to the target demographics for early PEV uptake. However, the corridor of a motorway (the A19 situated on the borders of Holystone and Valley) showed significantly high levels of City Adventurers compared to the rest of the Tyne and Wear region (93 City Adventurers compared to a regional mean of 14 per census output area). This essentially reflects the dominant influence of young professionals residing in such locations closer to motorway for convenience of commuting to workplaces in satellite towns and neighbouring business districts, using link routes.

< Place Figure.5 here>

Mapping Corporate Chieftains through census data set was particularly challenging, mainly owing to unavailability of data sets that could co-determine spatial distribution of detached houses as well as location of population with the highest NS-SeC rating. This was overcome by combining two separate data sets in a GIS layer, symbolising the most likely locations of this mosaic type. The outputs suggest this resident group to be predominantly occupying peri-urban locations, marked with lower population densities compared to New Urban Colonists and City Adventurers cohorts (and in some wards with nil values) (Figure 5). This is in agreement with the number of detached housing in the census output areas being moderately correlated with the highest ward totals of NS-SeC category 1 rankings. This category was considered as the strongest cohort for early PEV adoption, independent of PCP infrastructures. Nevertheless, this information was deemed essential for developing a cost-effective installation plan, diverting resources to alternative locations instead of reinforcing PCPs in such areas with lower demand for on-street PCPs.

3.2 Charging Infrastructure Development

Having established the spread of potential early PEV users into the three earmarked cohorts in the study region on the basis of the adopted methodological framework, the next step of the analysis involved ascertaining the share of those users who would be directly benefitted from setting up of PCPs. An elimination approach was applied, first establishing the spatial distributions of users with private charging facility on their premises, followed by a detailed analysis of potential locations for PCPs through weighted-overlay spatial statistics, using a combination of criteria listed in Table 2 (Section 2.3.3).

The private charging hotspots (Figure 6) seem to map quite closely onto the spatial distribution of Corporate Chieftains, as this cohort was characterised jointly by the ownership of detached houses and possession of multiple vehicles (see Figure 1). The output zones were mapped alongside the major road network, the location of park and ride facilities (large circles) and the regional centres of commercial interest (stars; as defined in Section 2.3) in the case study area. As discussed in Section 3.1.2, it can be clearly noted that private PEV charging potentials are higher in peripheral residential locations, close to the main city centre but away from the park and ride and regional centres. Interestingly, the potential zones for locating PCPs, output from the weighted-overlay spatial statistics, show complete contrast (Figure 7) and somewhat complementary to the spatial distribution of private charging locations.

<Place Figure 6 here>

Based on the spatial assessment in Figure 7, two categories of potential PCP locations, of particular relevance to both the New Urban Colonists and the City Adventurers, were noted: one, inner-city residential locations; two, out-of-town parking lots and commercial centres. The ground validation exercise, utilising the interview questionnaire (Section 2.3.4), indicated a good agreement with our spatial mapping from multi-dimensional analysis. Out of the total sample population (N=37) the majority of respondents were Corporate Chieftains (i.e. owning detached houses) who expressed their willingness to buy either a second car operating on BEV technology alongside their main vehicle operating on conventional fossil technology or investing in PHEV technology. In both cases this group of respondents were interested in using off-street trickle charging facilities on their own premises. On the other hand, the respondents with no 'home-charging' facilities were relatively smaller in number (N=11) and clearly expressed the limitation of parking space for more than one car and their unwillingness to install charging socket at home despite their interest in adoption of PEV technology. This was inferred as their motive of getting PEV as their main car with sole reliance on PCPs (either on-street in public bays or in work places) for their charging needs. The following sections describe the design recommendations for these two categories of PCPs and their potential usage. Apart from serving the users with restricted off-street charging facilities (identified above) it is envisaged they would be useful for Corporate Chieftains as either 'top-up' charging or as 'visible comfort for curbing the range anxiety' issues and would also offer charging provisions to long-distance car users travelling to the region from other parts of the country.

<Place Figure 7 here>

3.2.1 Inner-city locations

Depending on their locations, PCPs in inner-city regions are aimed to cater to the needs of the local residents as well as shoppers and employees. We have shown a high proportion of the early PEV users to be residing in inner-city regions, typically New Urban Colonists and City Adventurers with limited off-street parking. In these locations it would be crucial to provide access to on-street PCPs. Otherwise, although it has been concluded that early uptake of PEVs in such areas is likely, the lack of overnight charging could become a significant deterrent for mass uptake. For effective implementation, ideally each residential street with high uptake potential would have to be installed with PCPs. This would serve two purposes - one, generate PEV awareness and best practice; two, provide a dedicated parking space for PEVs which would be highly beneficial for end users overcoming the insecurity issues in finding parking space in such areas [30]. It is envisaged, both these initiatives in turn would potentially induce further PEV uptake.

Implementation plans for developing dedicated PCPs, especially for on-street charging, are already well underway for inner London as part of 'on-street parking location plan' [32]. These designs have prioritised both good visibility and good access to the parking bay for promoting early uptake. Such PCPs are located at either end of terracing, primarily because the end bay offers good visibility and easy access for users. In addition, high footfall from any adjoining main road is also potential for developing highly visible PCPs, creating further awareness. Overall, such infrastructure design is aimed to raise awareness and create growth in the PEV market. For practical reasons the locations of such on-street PCPs in residential areas would be more appealing than those situated in isolated car parks. In addition, access to overnight charging would be also relevant to the economy of PEV users through provision of off-peak tariff.

3.2.2 Peri-urban locations

The consumers of public PCPs in peri-urban locations would be most benefitted from installations in public car parks, park and ride facilities and regional centres of amenities, business parks, and local supermarkets. This would potentially also instigate usage by local residents frequenting these locations, specifically combining with the shopping and leisure activities. As shown in Figures 3 and 4, one of the most highly populated areas for New Urban Colonists and City Adventurers in the study area is located in the top-central part of the region, just on the outskirts of Newcastle. These areas have several park and ride facilities (Figure 1) which hold huge potentials for enhancing the PEV uptake to the target groups living in these locations with shortage of off-street charging facilities. Typically, following the London guidelines on ‘public car park location plan’ [32], up to two PCPs are recommended as best practice for installation in public car parks (usually recommended to be close to entrances or exits). This is in agreement with earlier studies recommending installations of PCPs in workplace parking, park and ride sites, retail areas and leisure facilities [8,11]. However, it has been suggested that cities should only design PEV strategies suiting their individual circumstances, mainly socio-demographics and parking availability [11].

The abovementioned implementation plans for developing dedicated PCPs can be extended to other global cities with similar urban driving patterns as discussed in Section 3.1. Combining this initiative with adequate provision of local renewable energy supply in peri-urban regions (e.g. wind, biomass, tidal) would facilitate building of a ‘balanced system’ for charging PEVs, supported by local energy from renewable sources. Some sites in the region can be classed as high value commercial locations for installing PCPs, which apart from serving the requirements of the two earmarked cohorts relying on public charging, would also generate further awareness and appeal for rapid PEV uptake in the region. Further, as can be noted from Figure 1, a number of hotspot locations serve as major commercial hubs in the region, thus strengthening the awareness for potential early adopters by appropriate selection of installation sites within these car parks.

4. Conclusions and Future works

Implementation of a well distributed PCP infrastructure is essential, both for supporting PEV drivers and for promoting a sustainable PEV market. In terms of public infrastructure development, especially borne out of the current austerity measures, strategic PCP locations would pave way for furthering the PEV agenda by reducing the range anxiety while facilitating on-street charging solutions. Crucial to the successful implementation of PCPs, however, is the availability of information on the projected spatial profiling of would-be PEV users who are lacking off-street charging.

This study adopted a multi-dimensional spatial modelling framework, utilising a combination of socio-demographic traits and travel patterns, to determine hotspots of PCP locations for a city-region. The applicability of this approach was demonstrated through a case study, utilising real datasets for the city-region of Tyne and Wear County in the North-East England. In the absence of any established metrics a combination of indicative census statistics were used to identify three categories of potential PEV users – New Urban Colonists, City Adventurers and Corporate Chieftains. These cohorts are considered as representative of typical city dwellers interested in adopting low-carbon transport measures.

Our study showed the capability of the modelling framework to predict the spatial distribution of private and public charging needs across a city-region, based on assumptions of early PEV adoption potentials. Locating zones with high private PEV charging potentials were helpful in demonstrating the non-urgency for installing PCPs in these locations, as it is anticipated such households will have access to overnight charging on their private premises. Specific to innovation in urban planning, our study showed two categories of potential PEV users utilising PCPs. First, a general uptake potential in the inner-city residential pockets with on-street parking, marked by New Urban Colonists and City Adventurers. These areas were identified as worthy of public infrastructure development in the targeted wards in the immediate future. Second, out-of-town public parking facilities, covering non-residential premises with opportunities for promoting PEV charging in parking bays or at park and ride facilities. We consider the multi-criteria assessment framework applied to this study equally extendable to other metropolitans and megacities across the globe with comparable socio-demographics and travel patterns (primarily commuting using personal transport). It is also felt that apart from serving the first generation of PEV users the extensive development of PCPs will also reduce range anxiety for those considering purchasing into the market. However, this study mainly demonstrated an integrated approach for linking the socio-demographics with forecasting of the hotspots of PEV uptake using geo-spatial analysis. The spatial analysis provides key insights into PCP allocations in the case study area. While extending this exercise to other cities it is recommended that the assessment framework is customised to utilise the publicly accessible statistics in a similar hierarchical structure in order to retain the effectiveness of the multi-dimensional analysis. In addition, a detailed roll out plan warrants further assessment of the implementation costs of installing PCPs at preferred locations. This would involve decision on the distribution and the kind of PCPs to be located, applying the principles of spatial economics. For example, location theory could be utilised to address the following specific operational questions: How many and what type of PCPs would be required? What precise location and design would optimise the economy of scale and multi functionality? What would be the total cost of such a system? All this has to be targeted in potential PEV uptake areas serving the two cohorts - New Urban Colonists and City Adventurers - where public charging point installations is found to provide the most impact.

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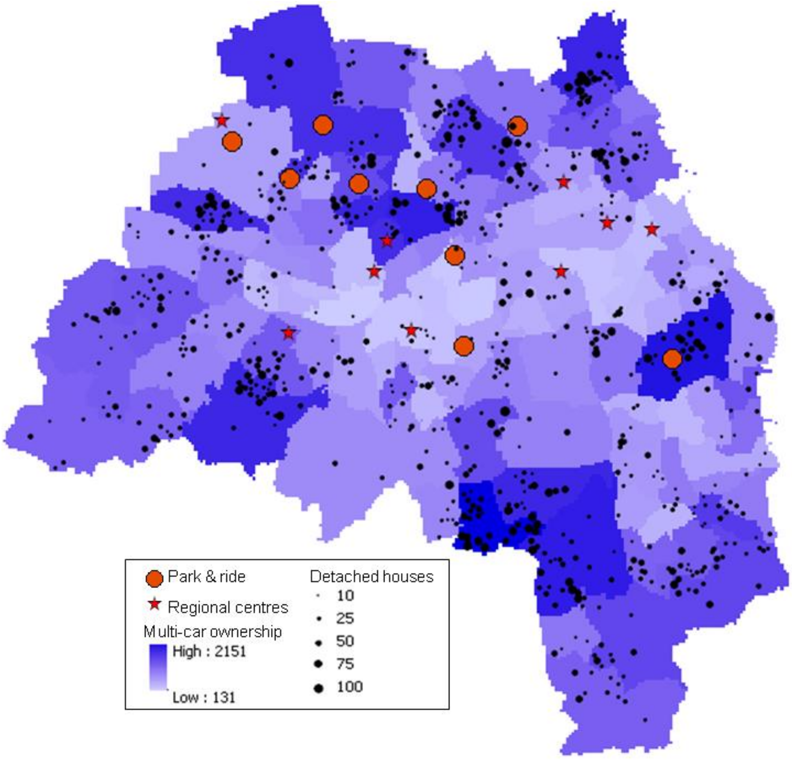
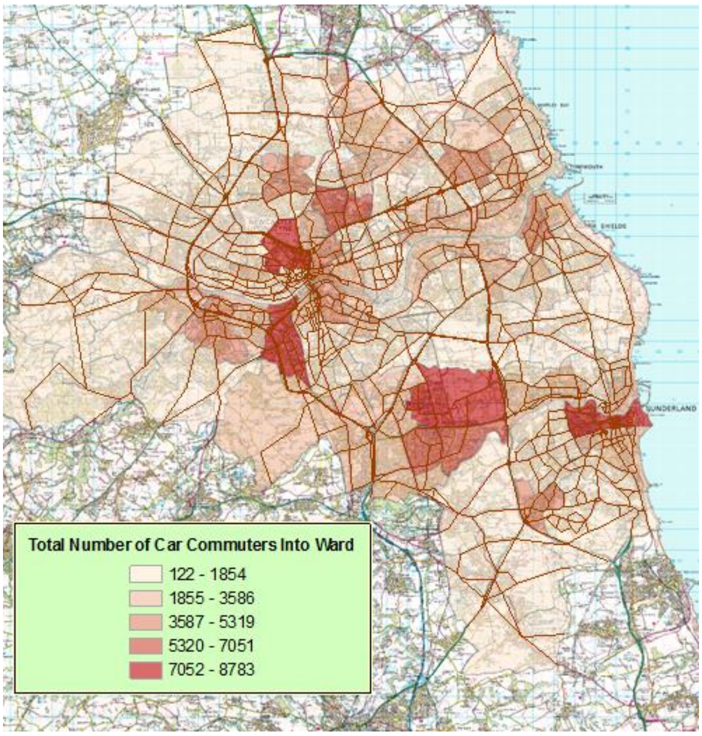
Fig 1



Park & ride
Regional centres
Multi-car ownership
High : 2151
Low : 131
Detached houses
10
25
50
75
100

Fig 2



SUNDERLAND
Total Number of Car Commuters Into Ward
122 - 1854
1855 - 3586
3587 - 5319
5320 - 7051
7052 - 8783

Fig 3

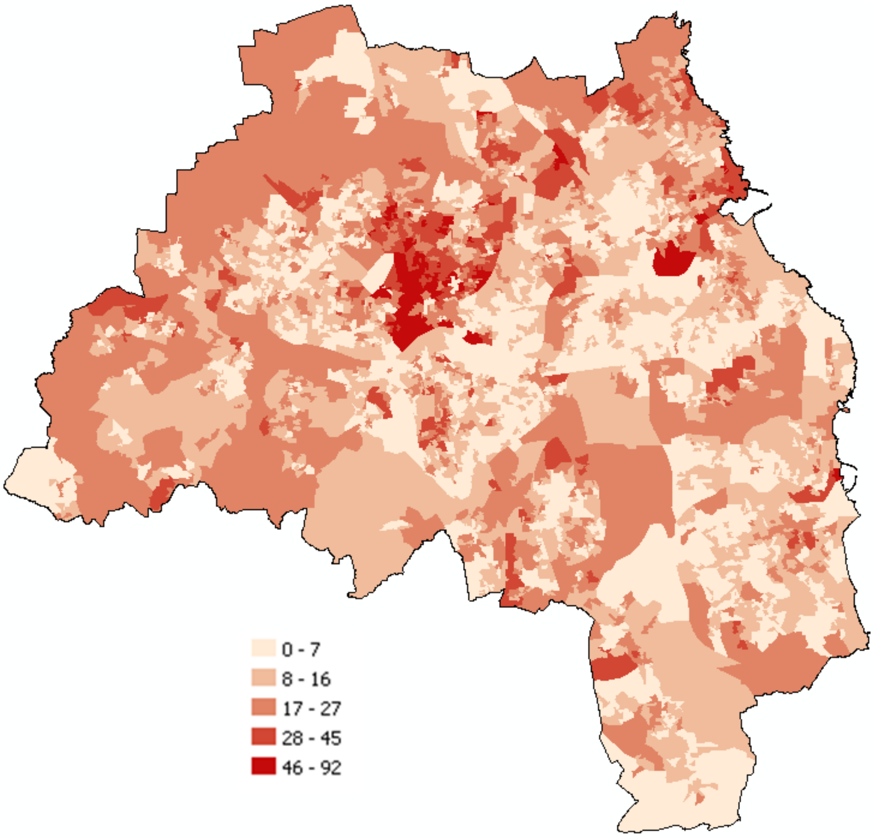


Fig 4

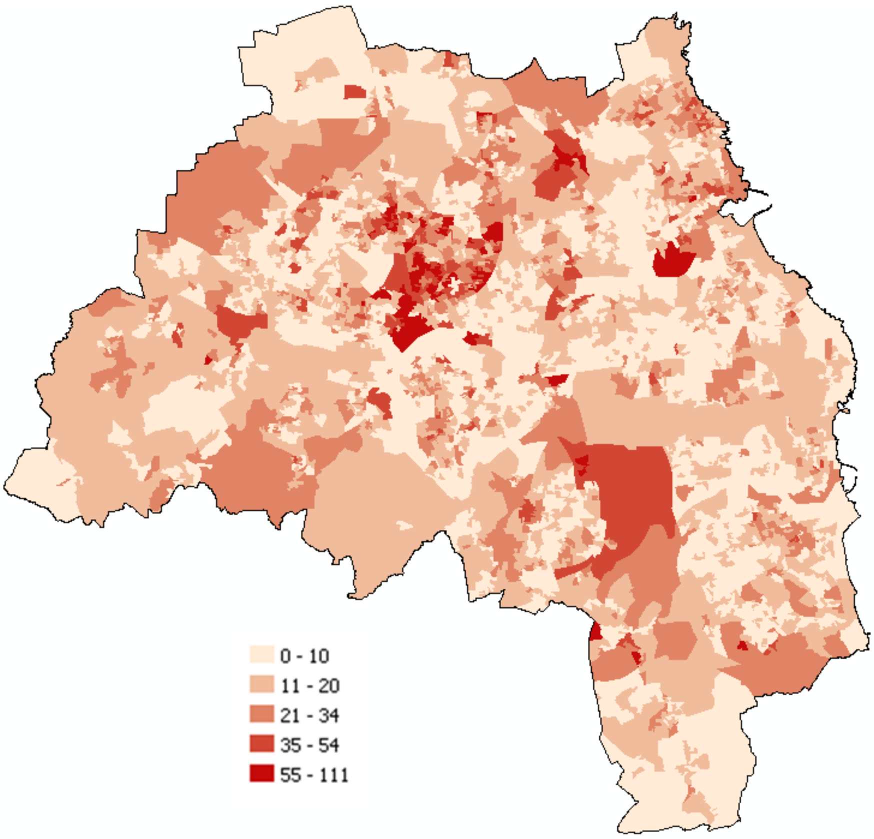


Fig 5

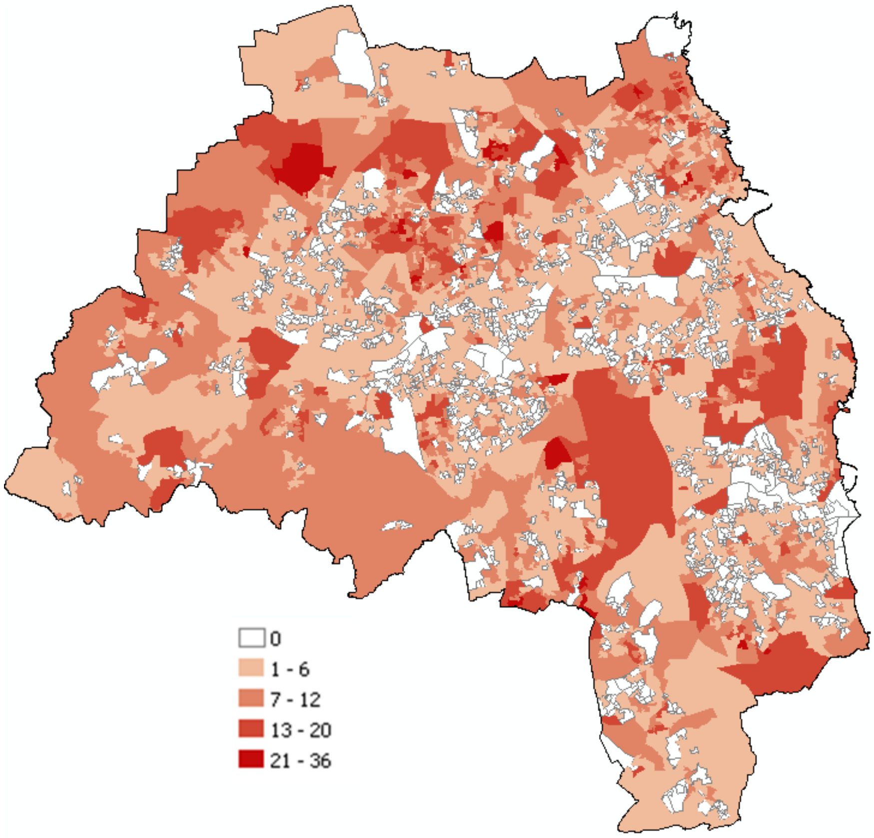


Fig 6

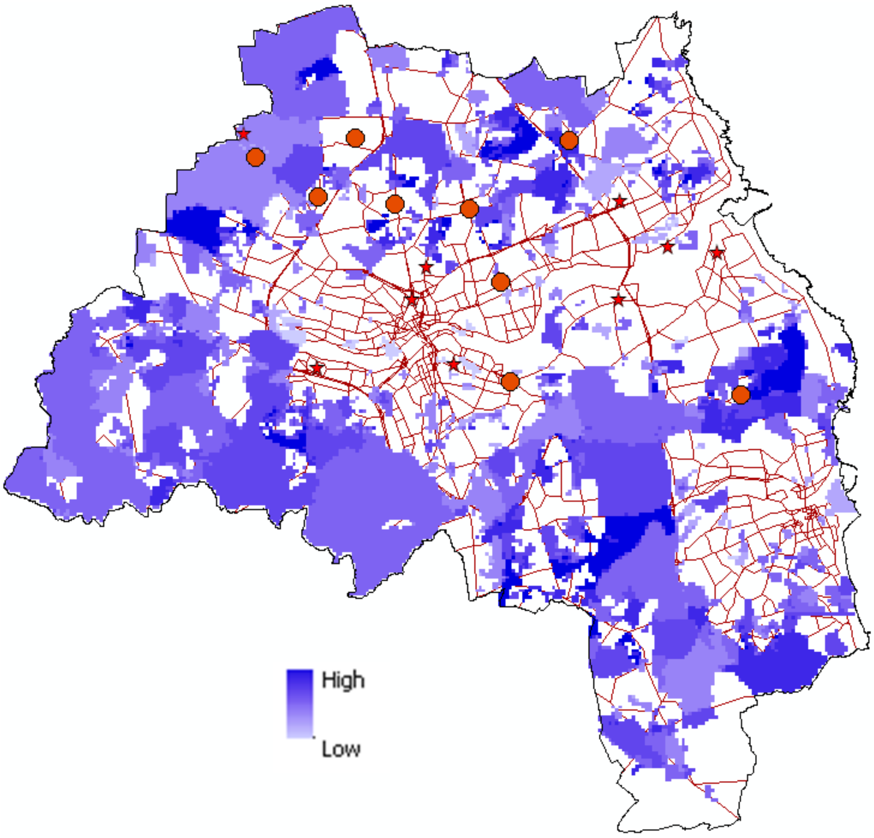


Fig 7